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Applicant	:	Yoichi Matsubara et al.	
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Customer No.	:	040854	

DECLARATION UNDER 37 CFR 1.132

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

Purpose of Declaration

This Declaration is being submitted to establish that disclosures made in the publication entitled "A Pressure Wave Generator for Pulse Tube Cooler" by Matsubara et al. (copy attached), which were relied upon by the Examiner in an Office action mailed on January 12, 2006 (Paper No./Mail Date 20060109) to reject claims 1-6 under 35 U.S.C. §102(a), are a description of applicant's own work and thus cannot be cited against the present application. See M.P.E.P. §715.01(c).

Facts and Documentary Evidence

The undersigned, being all of the inventors named in the present application, hereby declare that the all of disclosures made in the attached publication, which were relied upon by the Examiner in the Office Action mailed on January 12, 2006, are a description of applicant's own work. The authors of the publication are: Y. Matsubara; W. Dai; H. Sugita; and S. Tooyama. The inventors named in the present

application are: Y. Matsubara; H. Sugita; and S. Tohyama[1]. W. Dai is the only author listed on the Matsubara publication who is not included as an inventor on the present application. W. Dai was working under the direction of Yoichi Matsubara, Shinichi Tohyama, and/or Hiroyuki Sugita. He did not conceive of the invention or make any conceptual contributions to the invention as claimed, and thus is properly not named as an inventor of the subject matter claimed in the present application.

Declaration

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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1 It is noted that S. Tooyama and S. Tohyama are, in fact, the same person, as the phonetic translation of the family name is accurately spelled either way.

(14)

A Pressure Wave Generator for Pulse Tube Cooler

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ABSTRACT

This paper describes a concept of the pressure wave generator for the pulse tube cooler without use of the mechanical compressor. To understand the basic mechanism, work amplifier was fabricated and tested. It consists of work input piston, regenerator with heat exchanger on both sides, work transfer tube, resonator, and the work receiver. These five critical components are connected in series. The pressure wave is generated by the piston with the resonance frequency of the resonator. By heating the heat exchanger, which is located at the work transfer tube side of the regenerator, the input work from the piston is amplified through the regenerator and flows out from the work transfer tube due to the conversion of the heat flow into the work flow. This amplification mechanism makes it possible that the input work could be replaced by a part of this output work through the feedback line. Finally, it becomes a self-actuated pressure wave generator without any external input work.

This study mainly discusses the performance of each component to improve the total performance of the system. A simplified analytical method using the equivalent PV work and preliminary experimental results are also given.

INTRODUCTION

There are three different types of pulse tube cooler from the view point of the pressure wave generator: Stirling type uses directly driven mechanical piston, GM type uses circulating gas compressor with pressure switching valves such as the rotary valve, thermoacoustic or VM type uses thermal compressor instead of the mechanical compressor. This third type pressure wave generator can be further classified as follows:

(1) Standing wave type based on stack instead of the regenerator.
(2) Looped type having the circumference of the sonic wavelength of its resonance frequency.
(3) External long resonator with small feedback loop.
(4) Mechanical displacer with work transfer tube.
(5) Mechanical resonator with a feedback loop.

First one is well studied as the thermoacoustic pressure wave generator for the pulse tube coolers since 1988 [1, 2]. The thermodynamic efficiency of this method, however, is rather lower than the other progressive wave types which use regenerator instead of the stack. Second and third one are respectively developed by Yazaki and Tominaga [3], and Backhaus and Swift [4] as progressive pressure wave generators. Because of the relatively large resonator size, researches on these methods are intended for relatively large-scale applications. Fourth and fifth one are not well studied yet. However, the low frequency mechanical displacer, such like that of VM cycle has been studied recently. This paper mainly focuses on the basic performance of the resonator system using the solid displacer as a part of the pressure wave generator.

BASIC OPERATION PRINCIPLE

Figure 1 shows the basic concept of work flow amplifier. It consists of the work input piston, regenerator having heat exchanger on each side, work transfer tube, resonator and work output piston. This output piston can be replaced by a set of orifice and reser voir as shown in the figure. If the resonator is not connected and each piston is linked properly, it becomes a Stirling type pulse tube cooler or a prime mover (without hot piston), which depends on the heat exchanger temperature at the junction of the regenerator and the work transfer tube. In the case of the orifice and the reservoir, it becomes orifice pulse tube cooler or simple work amplifier.

If the resonator is connected as shown in figure 1, the orifice pulse tube cooler become an inertance type pulse tube cooler, which gives better thermodynamic performance. In general, the phase shifter used in the inertance type consists of a narrow long tube and the reservoir in series. However, this parallel configuration could become an alternative. Here the resonator 1 and 2 are arranged symmetrically to eliminate the mechanical vibration caused by each displacer's movement.

If the heat input at the heat exchanger, Hxh, increases until the temperature exceeds the room temperature, it become a work amplifier. The input work from the piston is amplified through the regenerator and flow out from the work transfer tube due to conversion of the heat flow into the work flow. In this case, the function of the resonator becomes more important. To have a better understanding of this effect, following simplified numerical analysis has been done.

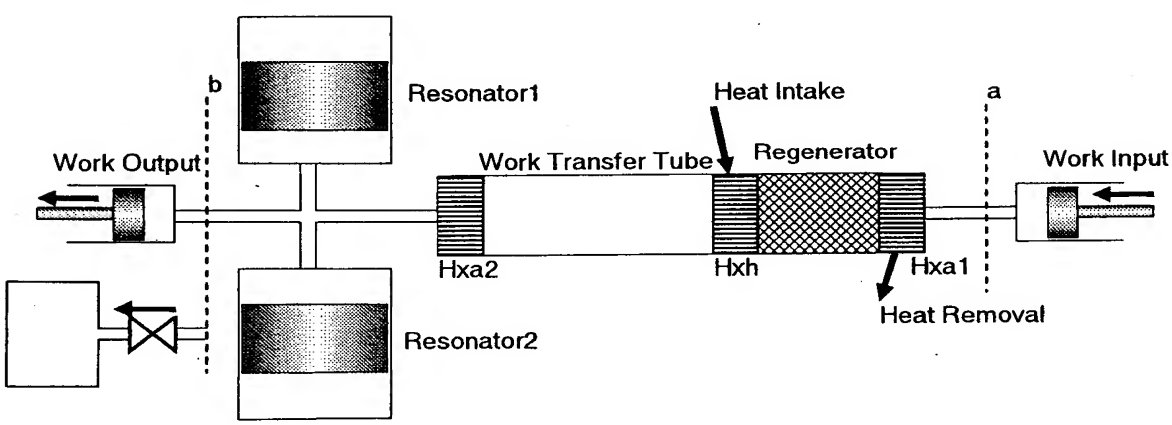

Figure 1. Schematic arrangement of work amplifier.

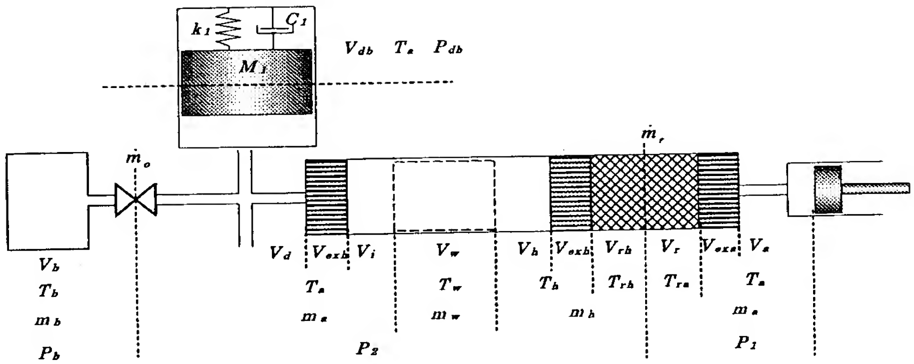

Figure 2. Notations used in equations

Simplified Analysis

The ideal gas assumption (gas constant: R) was used for following equations. The notation is given in figure 2.

Momentum equation of the displacer: $M_1 \dfrac{d^2x}{dt^2} = -\left\{ C_1 \dfrac{dx}{dt} + k_1 x - A_1 \left(P_2 - P_{db}\right) \right\}$,

Pressure equation at the work transfer tube: $P_2 = R \dfrac{T_a(m_a + m_o) + T_w m_w + T_h(m_h - m_r)}{(V_d + V_{hxa} + V_{wt} + V_{hxh} + V_{rh} T_h / T_{rh})}$,

Pressure equation at the backside volume V_{db}: $P_{db} = R \dfrac{m_{db} T_a}{(V_{db} - Ax)}$.

Pressure equation at the work input piston: $P_1 = R \dfrac{T_a(m_a + m_r)}{(V_a + V_h + V_r T_a / T_{ra})}$,

where the oscillating volume is given as the boundary condition as: $V_a = V_{a0} + V_{a1}\sin(\omega t)$.

Orifice mass flow equation: $\dot{m}_o = C_o(P_b - P_2)$,

Pressure in the reservoir: $P_b = R \dfrac{T_a(m_b - m_o)}{V_b}$

Regenerator mass flow equation is simplified as: $\dot{m}_r = C_r(P_2 - P_1)$,

where C_r, is the equivalent flow coefficient given at the middle of the regenerator. Example calculation in the case of using orifice and the reservoir as the work receiver has been done with the following input parameters in Table 1.

Table 1 Input parameters of example calculation

sizes	Input Parameters
Displacer weight, M_1 = 1.85 kg (x 2)	T_h= 600 K
Spring constant, k_1 = 6.58 kg/cm (x 2)	T_a= 300 K
Displacer frontal area, A_1 = 21.2 cm^2 (x 2)	Initial pressure = 1.5 MPa
Displacer backside volume, V_{db} = 450 cm^3	C_r= 30.0
Work transfer tube volume, V_{wt} = 263 cm^3	C_o= 5.0
Regenerator void volume, V_r= 86 cm^3	C_1=0.001
Heat exchanger void volume, V_{ex} = 20 cm^3 (x 3)	----------------------------
Reservoir volume, V_b= 250 cm^3	$V_a = V_{a0} + V_{a1}\sin(\omega t)$
	V_{a0}=40 cm^3 V_{a1}= 5 cm^3

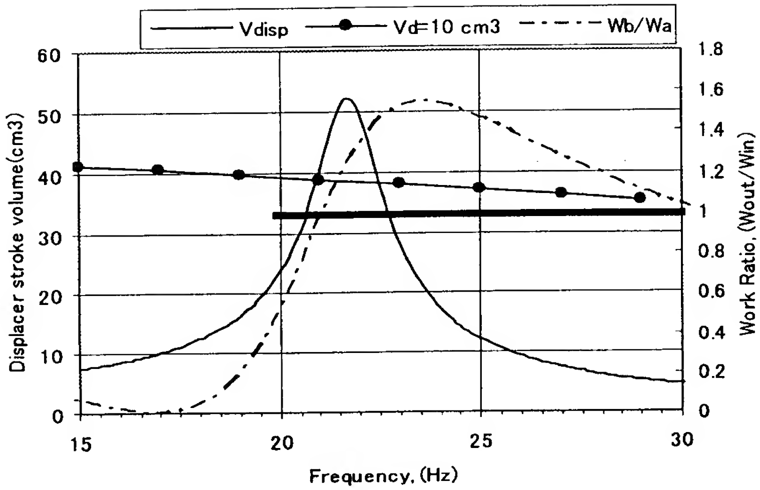

Figure 3. Frequency dependency of displacer stroke and gain of work output

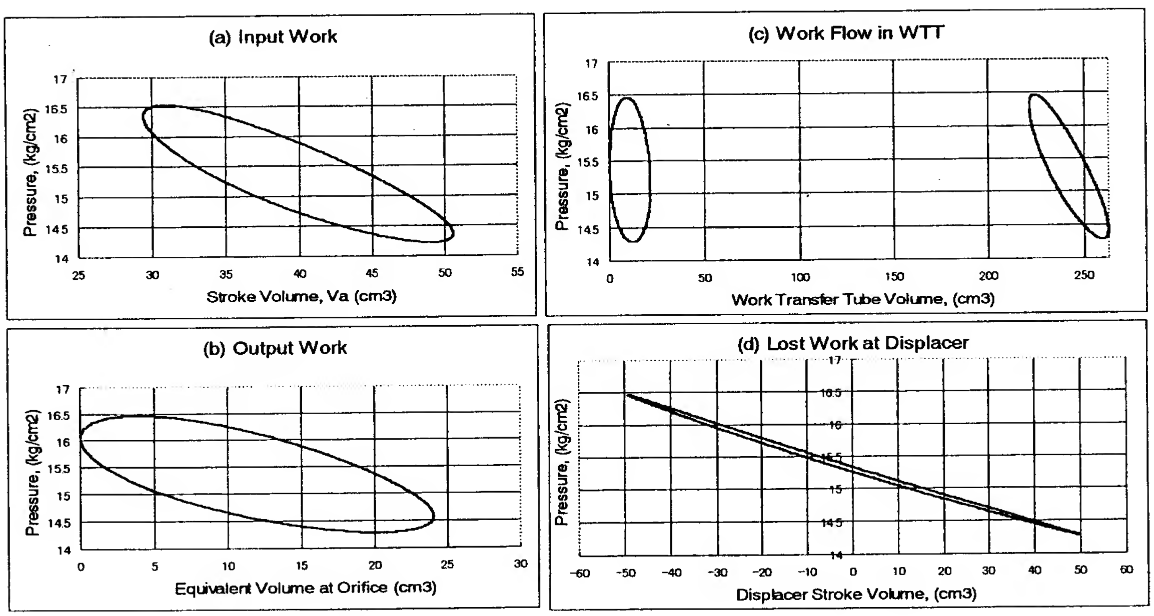

Figure 4. Calculated results of PV work

The result is given in figure 3. It clearly shows the existence of optimum driving frequency, which gives maximum work amplification. The maximum ratio of output work and input work is 1.54 at the frequency of 23.6 Hz. It is noted that the resonance frequency of the displacer does not coincide with this optimum frequency. If the displacer is removed, the work amplification ratio is represented by the line of V_d= 10 cm^3. This result indicates the effectiveness of using displacer as resonator.

Each equivalent PV work at the driving frequency of 24 Hz is shown in figure 4. Parameter s are the same with table 1 except V_{a1}=10.5cm and C_1=0.005. (a) is the input work at the compressor piston, (b) is the output work, which is the dissipated work at the orifice in this case. (c) is the equivalent work at the both end of the work transfer tu be. This example calculation indicates the size of the work transfer tube is large enough. (d) is the dissipated work at the displacer. This narrow PV shape indicates the high quality factor of the resonator to generate the standing wave.

The input work of 45.7 watts at the piston is amplified to 85 watts and passes through the work transfer tube to the orifice. The lost work at the displacer is 14.5 watts. This relatively large loss is due to the assumption of large value of C_1. However the output work is 70.2 watts and the ratio of 1.54 is still remained.

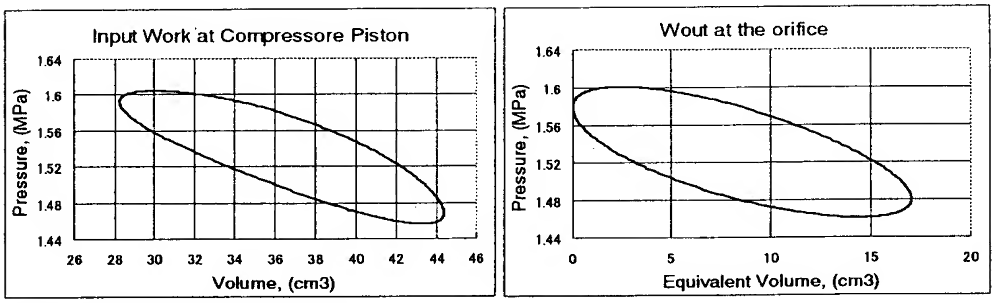

Figure 5. Measured PV works

EMPIRICAL DEMONSTRATION

An experimental test device was fabricated. Each component size is same with data of table 1. One preliminary test result is given by figure 5. The driving frequency is 24.5 Hz with V_{a1}=8 cm^3. Heating temperature Th is 556 K and Ta is kept around 300 K. Orifice Cv Value is 0.2. Measured input work at the compressor piston was 25.5 watts and the output work at the orifice was 33.1 watts. The work amplification ratio of 1.3 has been obtained.

SELF ACTUATED SYSTEM

Figure 6 shows a possible arrangement of self actuated pressure wave generator. Since the output work in figure 1 is larger than the input work at the optimum driving frequency, the input work could be replaced by a part of the output work through feedback line. As the result, external work input is no longer required and the whole system becomes a self-actuated pressure wave generator without any external input work. Here, the orifice and reservoir as a work receiver could be replaced by a pulse tube with the regenerator.

Simplified analysis

Instead of the compressor equation: $V_a = V_{a0} + V_{a1}\sin(\omega t)$, another momentum equation,

$$M_a \frac{d^2 x_a}{dt^2} = -\left\{ C_a \frac{dx_a}{dt} + k_a x_a - A_a \left(P_1 - P_2\right) \right\}$$

could be applied to solve the system such like the figure 6.

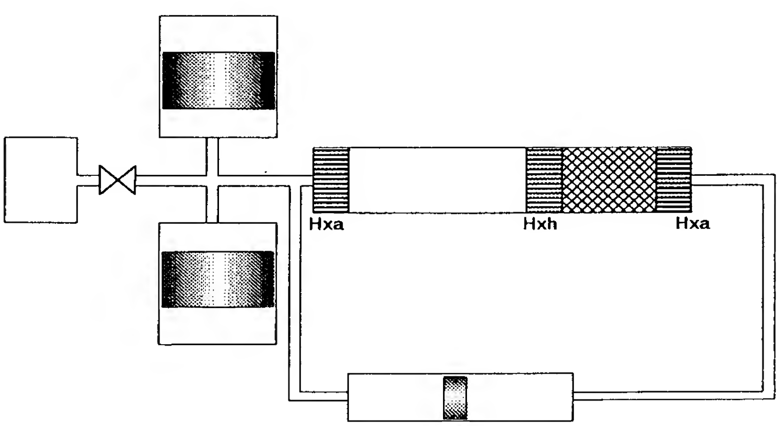

Figure 6. Possible arrangement of self actuated pressure wave generator with feed back loop.

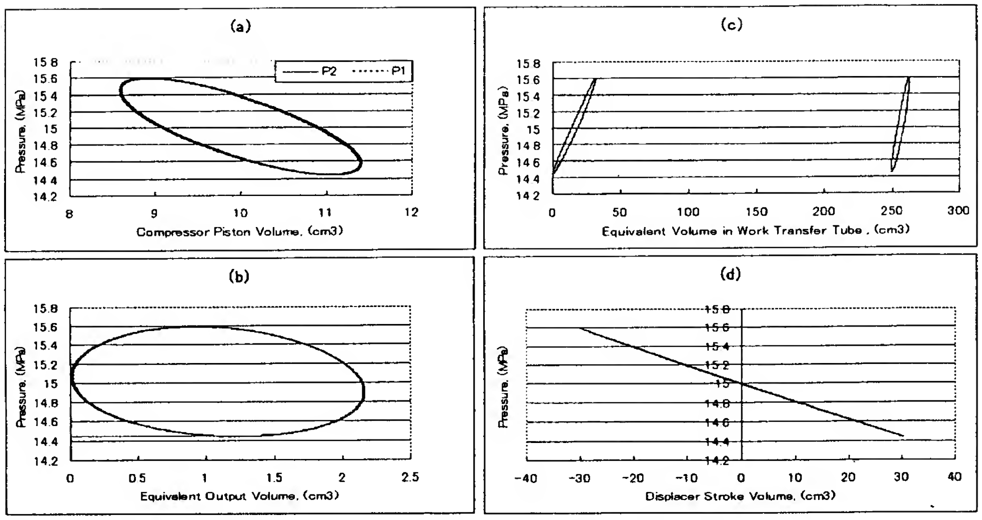

Figure 7. Calculated result of PV work for self actuated oscillation mode

Here the solid mass M_a is used for the convenience of numerical analysis. An example calculation has been done using the same parameters of table1 with additional parameters: M_a=0.5 kg, C_a=0.01, k_a=0.1 kg/cm, A_a=25 cm^2. Other parameters different from table1 are, Th=800 K, V_{db}= 620 cm^3, Co=0.7.

Self-actuated oscillating frequency is 21.6 Hz. Work flow within the work transfer tube of 36.7 watts is obtained. The lost work at the displacer is 3.3 watts and the output work is 18.3 watts. The feedback work to the additional solid displacer is 14.7 watts, and then it is reduced to 14.6 watts and supplied to the regenerator.

CONCLUSION

This article discussed the possibility of self-actuated pressure wave generator using solid displacer. As the first step, experiments of using the mechanical compressor as external work input has been done. Work amplification effect has been verified. The result is well explained by the numerical analysis. Based on these, design of self-actuated pressure wave generator has been presented and numerically verified.

The inertance effect of the work flow feedback line is essential for realizing the self-actuated pressure wave generator. Further experimental study is required to confirm the calculated result.

ACKNOWLEDGMENT

We would like to thank Prof. De Waele (Eindhoven) for his helpful discussions.

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